Cloud and Aerosol Monsoonal Processes-Philippines Experiment ($\mathrm{CAMP^2Ex}$)

A proposed joint US-Philippine airborne mission to study aerosol and land use impacts on monsoonal precipitation during late summer 2018

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Executive Summary:

The Clouds, Aerosol, and Monsoon Processes-Philippines Experiment (CAMP^{2}Ex) is a proposed NASA airborne mission scheduled for summer 2018 to characterize the role of anthropogenic and natural aerosol particles in modulating the frequency and amount of warm and mixed phase precipitation in the vicinity of the Philippines during the Southwest Monsoon. In partnership with Philippine research and operational weather communities, CAMP^{2}Ex will provide a comprehensive 4-D observational view of the environment of the Philippines and its neighboring waters in terms of microphysical, hydrological, dynamical, thermodynamical and radiative properties of the environment, targeting the environment of shallow cumulus and cumulus congestus clouds. Three core NASA focus areas are embedded within the project:

1) *Aerosol and cloud microphysics:* To examine how aerosol particle concentration and composition effect the optical and microphysical properties of shallow cumulous and congests cloud, and how, ultimately, these effects relate to the transition from shallower to deeper convection.
2) *Cloud and Aerosol Radiation:* To study how spatially inhomogeneous and changing aerosol and cloud fields impact three dimensional heating rates and fluxes, and determine the extent to which 3 dimensional effects may feedback into the evolution of the aerosol, cloud, and precipitation fields.
3) *Aerosol and cloud meteorology:* Determine the meteorological features that are the most influential in regulating the distribution of aerosol particles throughout the regional atmosphere and, ultimately, aerosol lifecycle, and ascertain the extent to which aerosol-cloud interactions studies are confounded and/or modulated by co-varying meteorology.

In addition to these three core NASA basic research objectives, Philippine scientists in CAMP^{2}Ex will focus on the ramifications of monsoonal meteorology on regional hydrology, oceanography, and air quality.

The above science objectives will be addressed through the deployment of a NASA research aircraft (likely the P-3B) based out of Subic Bay, for ~120 to 150 research hours, in combination with data from an extensive constellation of polar orbiting, geostationary satellite and ground based sensors. Notable emphasis will be placed on data from Himawari-8 and Global Precipitation Mission (GPM) sensors. It is anticipated that active collaboration will occur between CAMP^{2}Ex and the Office of Naval Research sponsored Propagation of Intra-Seasonal Tropical Oscillations (PISTON) field campaign. The primary set of measurements required in this airborne experiment are defined by the need to characterize the cloud, precipitation and aerosol particle properties, as well as the associated atmospheric and cloud dynamics, and the fluxes of solar and terrestrial radiation. While CAMP^{2}Ex is primarily an aerosol-cloud-precipitation mission, appropriate consideration for variations in meteorology are a necessary and important focus.

1.0 Mission Motivation & Rationale for Policymakers

Southeast Asia is thought to be sensitive to climate change, with the Philippines being considered highly susceptible to hydrology related outcomes. Severe typhoons and intense monsoonal activity frequently bring dramatic flooding to the Philippines and receive considerable attention on an international level. On the other hand, periods of anomalous below-average rainfall, while less dramatic, also have significant adverse effects on the Philippine people and agriculture. Anecdotal evidence of a recent increase in the number of "no rain" days is now being scientifically corroborated. These changing climate conditions, with the increasing and changing population density, highlight the need to facilitate water planning and emergency response strategies. In such a rapidly changing region, it is critical to understand how both drought and flooding extrema will evolve.

Climatological studies of precipitation in SE Asia suggest that, contrary to the Intergovernmental Panel on Climate Change (IPCC) multi-model ensemble, SE Asia is experiencing decreasing precipitation over time. For example, *Endo et al.* (2009) noted the number of precipitation days with at least 1 mm of precipitation showed a decreasing trend during 1950s-2000s over SE Asia, particularly north of the Maritime Continent. Downward precipitation trends are also evident at stations in northern Borneo. *Cruz et al.,* (2013) found noticeable decreases in summer monsoonal precipitation in six of nine stations in the western Philippines after taking into account the impacts of the El Niño Southern Oscillation (ENSO). They also found an increasing trend in the number of days without precipitation, as well as a decreasing trend in the number of heavy rainfall days. The decrease in heavy rainfall days may be attributable to changes in tropical cyclone activity (*Kubota and Chan,* 2009). However, the cause of the change in no-rainfall days is still unknown. Similar studies in places such as Java (*Aldrian and Djamil*, 2008) and peninsular Malaysia (*Deni et al.,* 2010) have noted similar trends.

Aerosol particles are an important part of the hydrological cycle, serving as the nuclei for forming cloud droplets. While the literature clearly demonstrates the importance of large-scale flow patterns on precipitation, it has frequently hypothesized increases in anthropogenic and biomass burning emissions related to regional development to also impact precipitation. Variations in the natural aerosol population due to biological activity and sea salt generation are thought to be important, but are poorly understood. While many case studies demonstrate aerosol particles influencing precipitation from shallow to very deep convective clouds, the overall importance of this influence relative to large-scale meteorological forcing agents is largely unknown (*Andreae et al.,* 2004; *Khain et al.,* 2005; *van den Heever et al.,* 2006; *Tao et al.,* 2012). Ordinary cumulus and cumulus congestus clouds, fields of which are frequently observed over continental and maritime regions of Southeast Asia, appear to be affected by aerosol particles (*Yuan et al.,* 2011; *Li et al.,* 2010; *Sheffield et al.,* 2015). In very clean conditions, when the numbers of aerosol nuclei present in the atmosphere are very low, cumulus clouds consist of fewer but larger cloud droplets. These clouds tend to produce precipitation more frequently. Even small cumulus clouds are observed to precipitate in pristine conditions, as recently observed in the Rain in Cumulus over the Ocean (RICO) field campaign (*Rauber et al.*, 2007, *Snodgrass et al.,* 2009). In more polluted conditions, an excess of aerosol particles leads to larger numbers of smaller cloud droplets, and clouds which are generally less prone to precipitate. However, under certain conditions some of these clouds grow to extend above the freezing level, from where they can go on to produce severe thunderstorms (*Rosenfeld and*

Lensky, 1998, *van den Heever et al.,* 2006, 2011; *Wang et al*., 2009; *Morrison and Grabowski,* 2011). Atmospheric scientists do not currently understand cumulus cloud processes well enough to quantitatively predict cloud properties and behavior. The heart of the problem appears to lay in (1) complex ice phase microphysics within clouds, (2) difficulties in properly capturing the budgets for latent and radiative heating, and (3) feedbacks between cloud microphysical processes and mesoscale dynamics. Aerosol particles appear to impact all three of these factors. For example, clouds with high numbers of smaller droplets due to the presence of aerosols tend to lift more liquid water to an altitude where freezing starts compared to clouds with fewer numbers of larger droplets. Since the process of freezing releases latent heat, and latent heat generates stronger updrafts, the potential result of this positive feedback is a more intense thunderstorm.

The rapidly expanding economy in Southeast Asia produces in plumes of polluted air moving through an otherwise clean maritime environment. Summertime monsoonal flow transports pollution throughout the region; frequently to the Philippines. In addition, the Philippines hosts its own significant aerosol sources including urban centers, extensive shipping, and volcanic activity. The extensive cloud cover and complex meteorology of Southeast Asia makes monitoring in and modeling of this environment extremely difficult. However these same factors make the region an almost ideal natural laboratory in which to seek answers to the role of aerosol particles in tropical cloud systems. Key cloud processes, such as freezing, radiative processes and their ties to storm dynamics are not understood sufficiently well to predict the sensitivity of precipitation to aerosol particles or to assess how future severe weather events (floods and drought) will react to changing anthropogenic emissions and climate. To enable the development of responsible water and agricultural policies as well as effective emergency response plans, the consequences of changes in aerosol particle emissions and transport on precipitation must be understood. The region surrounding the Philippines is an ideal location to pursue this objective.

A core difficulty facing the scientific community is separating aerosol effects from those of co-varying meteorology. For example, biomass-burning emissions in the Maritime Continent increase during seasonal dry periods. Thus extreme dry periods lead to extreme biomass burning events. To infer how burning emissions affect the weather, the unaffected character and variability of the very weather that initiated and sustained the burning event of interest must be isolated. Similarly, land use change leads to changes in both surface characteristics and aerosol emissions, which also simultaneously affect the aerosol and meteorological environment. However, during the boreal summertime Southwest Monsoon, the region of the Philippines is subject to predictable large scale forcing of the meteorological environment. Further, sources of aerosol particles are confined to relatively small regions within the oceanic expanse. Thus this region is an ideal location to work toward de-convolving the physical processes and confounders controlling aerosol and cloud processes in the tropical environment.

2.1 Fundamental considerations for non-specialists on cloud-aerosol interaction

Qualitatively the fundamental processes by which clouds are formed have been understood since the 19th century, and are even taught in elementary schools. Key amongst them is the process of vapor condensing on aerosol particles (smoke being often used in classrooms to make this point) much sooner than it would in clean air, resulting in the formation of cloud droplets. On our planet, a variety of aerosol sources can act as more or less efficient attractors of water vapor (or 'cloud condensation nuclei'). Throughout the 20th century, atmospheric scientists advanced our knowledge of the nature most of the processes that lead to different cloud types, and the processes that initiate, sustain and modulate precipitation in its various forms. A number of interactions have been identified among and between vapor, cloud droplets, ice crystals, hydrometeors (a collective noun encompassing raindrops, hailstones, snowflakes and other falling ice particles) and the motions, temperature and moisture content of the air in which they exist. Differences in these interactions explain qualitatively why planet Earth is covered in a large but finite number of different types of clouds ranging from thin cirrus to deep thunderstorms.

At the most fundamental level, precipitating clouds can be classified as 'warm clouds' (i.e., those without ice, in general developing in the lowest few kilometers above the earth) and 'cold clouds' (clouds where the generation of precipitation is dominated by ice, even when liquid rain may reach the ground due to the melting of frozen hydrometeors). These two designations can be further subdivided. For example, 'shallow warm' clouds are less than a kilometer deep; 'cumulus congestus' have tops that are at or slightly colder than 0^{o} C and are mostly made of liquid cloud droplets and raindrops, but can also include significant fractions of ice; 'deep convective' clouds are often associated with strong thunderstorms, and among them 'overshooting' storms are those that are so tall they penetrate into the lower stratosphere (and are frequently associated with extreme weather). In this last category, water is likely to transition through the vapor, liquid and ice states cited above, and a variety of hydrometeor and water phases coexist in large portions of the cloud. Hail, lightning, and tornadoes can also result, depending on specific conditions.

As critical as these advances have been in the creation of modern day weather forecasting models, significant uncertainties remain in the *quantitative* aspects of the aerosol-cloud-precipitation processes. For example, the amount of heat released when a raindrop is lifted in a thunderstorm and completely freezes is well known. However, it is more difficult to predict how long it will take to fully freeze and release its latent heat or at what altitude the release of latent heat will occur. This uncertainty is due to turbulent airflow inside the cloud as well as probable collisions with other hydrometeors. Cloud droplets continuously interact with other droplets within the rapidly changing environment of the cloud. The complexity added by these processes is one among many causing significant errors in weather model predictions of surface precipitation type and amount.

While Chaos Theory may impose limits on weather (and climate) predictability, the notion our current forecast ability cannot be improved is unreasonable. For example, hurricane track forecasts have steadily improved over the last two decades to the point where the location of hurricane landfall can be predicted to within 100 nmi as much as 3 days ahead (Joint Typhoon Warning Center, personal communication). Forecast models can now make such predictions because they include significantly more detail of the physical processes of such storm systems. Furthermore, improved observational datasets have resulted in better model initialization, improved parameterizations and more tightly constrained solutions. However, a significant perturbation in the number of aerosol particles within a region can lead to significantly altered outcomes, both in the real world and model simulations. The sensitivity to aerosol load is primarily due to the extremely non-linear nature of the processes involved. In Earth's atmosphere, water changes phase (gaseous vapor, liquid water, solid ice) in discrete 'jumps' when thresholds are crossed. Every time the phase of water changes, energy is released or absorbed, radiation is blocked or allowed to pass, and water either falls back to the earth's surface through the chain reactions that lead to precipitation, is injected into the stratosphere by means of violent and deep vertical motions inside storms, or is transported thousands of miles away in the form of a non-precipitating cloud. In turn, the destiny of one particular storm or cloud affects the destiny of its neighbors via its effects on radiative heating and cooling (e.g., the presence or absence of cloud cover), injection or depletion of moisture in the environment, and general perturbation of the local circulation of air masses. For these reasons, improved quantitative knowledge of at least the key interactions between dynamics (i.e., the vertical and horizontal motions within the storm) and microphysics (i.e., the evolution of hydrometeors) is necessary to improve the model's skill in assessing the probability of floods, flash-floods and other extreme events.

In order to address important issues, maintain clear project scope and achievable objectives, CAMP^{2}Ex will focus on shallow warm cumulus clouds and congestus clouds, as they occur in the rich and somewhat predictable environment of the Southwest Monsoon around the Philippines. This natural laboratory is described in detail in the next section. The primary reason for choosing shallow warm cumulus clouds and congestus lies in their predicted high sensitivity to aerosol loading and tractability to hypothesis testing. Shallow warm cumulus clouds consist entirely of water vapor and liquid water. Aerosol particles appear to have a significant impact on their precipitation processes, and may at times completely inhibit rainfall. The relative simplicity of these two-phase clouds facilitates untangling aerosol impacts on precipitation without the added complexity of ice. Congestus clouds are mostly warm phase clouds, however, they can contain ice and are likely the most dynamically simple of the mixed phase clouds. Two modeling studies (*Li et al.,* 2010; *Sheffield et al.,* 2015) have recently suggested that the additional latent heat released during the formation of more droplets in polluted conditions results in more frequent growth of congestus clouds to above the freezing level, and hence the formation of more ice. As more ice is formed, more latent heat is released, and these invigorated congestus may go on to form deep convective clouds. Examining congestus clouds, therefore, allows for an assessment of the impacts of aerosol particles on the most simple of the mixed phase clouds, and on their transition from warm phase to mixed phase systems. Deep convection will also be observed and characterized, mainly to put the measurements of shallow and congestus in their proper context (e.g., the lifecycle of the cloud, influences of deep convection on the environment around more shallow surrounding clouds, and to contrast conditions). In order to untangle the various contributors to the evolution of a cloud, and to isolate and characterize to a statistically significant level as many threshold parameters as possible, CAMP^{2}Ex will observe these clouds repeatedly and in various contrasting environmental conditions and aerosol loadings. The richness of occurrence offered by this part of the world is key in the selection of the site: in order to achieve statistical significance, these observations need to be repeated multiple times.

2.2 Considerations of the Southwest Monsoonal System

Much of the precipitation in the northern Philippines is associated with the so-called "Southwest Monsoon". The northern-hemisphere summertime Southwest Monsoon categorizes a roughly mid-April through mid-October period when the Inter Tropical Convergence Zone (ITCZ)/monsoonal trough is north of the Maritime Continent, and consequently the South China and Sulu Seas typically have southwest winds at the surface (that is, in the Marine Boundary Layer, MBL) that veer to the west in the lower free troposphere above the MBL (e.g., up to 4 km in altitude). The air reaching the inter-tropical convergence zone (ITCZ, aka monsoon trough) or significant storms in the Southwest Monsoon are pumped up to the top of the troposphere by convection, resulting in a northeasterly return flow in the upper troposphere. This simple system comprises the wet season in the northern Philippines. This monsoonal period also coincides with the drier season for the southern Maritime Continent (i.e., Borneo, Sumatra and the Malay Peninsula) and consequently enhanced regional biomass burning activity. Since drier periods imply reduced scavenging of aerosol particles by rain, aerosol particles are transported over longer distances from the Maritime Continent up the South China, Sulu and Celebes Seas as a result. Taken as a whole, the Southwest Monsoon connects drier and more polluted conditions in southern Maritime Continent to wetter conditions in the northern Philippines and ultimately the monsoonal trough. In between these two regions lies a transition zone that spans from drier to wetter, and from more polluted to cleaner; perhaps even to clean oceanic background.

Multiple review papers describe key meteorological features of the southwest monsoonal system (*Chang et al.,* 2005, and *Moron et al*., 2009). In addition, numerous inter-annual, inter-seasonal to mesoscale phenomena related to the southwest monsoon are reported in the literature (e.g., *Mao and Chan*, 2005 and reviewed by *Wang et al.,* 2009). Notable meteorological components include El Niño-Southern Oscillation (*Ju and Slingo*, 1995; *McBride et al.,* 2003), the Madden-Julian Oscillation (MJO); (*Zhang and Dong*, 2004; *Zhang,* 2005), monsoonal flow related convergence at coast lines and associated convection (*Nugent et al*., 2014), quasi-monthly oscillation (QMO); (*Wang et al.,* 2006), and tropical cyclones (*Cayanan et al*., 2011). Relationships of some of these phenomena to aerosol emissions and their lifecycle have been outlined at similar scales including ENSO to monsoonal scales (e.g., *Nichol*, 1998; *Field and Shen* 2008; *Reid et al.,* 2012; *Xian et al.,* 2013), the MJO (*Tian et al.,* 2008; *Reid et al.,* 2012), and even tropical cyclones (*Reid et al.,* 2012, 2015; *Wang et al.,* 2013). Complicating the connection between the aerosol and meteorological phenomenon are a host of finer scale features, such as the sea breeze circulation which modulates how aerosol laden air masses transition from terrestrial to maritime environments (e.g., *Mahmud et al*., 2009 a & b; *Wang et al.,* 2013) and back again (e.g., *Grant and van den Heever*, 2015), to individual cold pools (*van den Heever and Cotton,* 2007; *Lee et al.,* 2008; *Storer et al*., 2010; *Seigel and van den Heever*, 2012; *Grant and van den Heever,* 2015; *Saleeby et al*., 2015); and organized squall lines (*Reid et al*., 2015). It is at these scales that meteorological and aerosol environments are fundamentally linked.

Examples of larger scale phenomena resulting in active and suppressed emissions and/or convection at the inter-annual scale are provided in Figure 1. Figure 1 (a) and (b) provide August through September 10-m above-surface winds for 2006 and 2007 mapped on corresponding CMORPH precipitation from *Xian et al.,* (2013). The years 2006 and 2007 represent a shift in one year from moderately warm (i.e., Oceanic Niño Index = +0.5^{o}C => El Niño) and moderately cool (Oceanic Nino Index = -0.8^{o}C => La Niña) ENSO phases, respectively. Wind and precipitation fields demonstrate the overall nature of the monsoon. A monsoonal trough is clearly visible east of the Philippines. Easterly winds south of the equator transition into the monsoon's characteristic southwesterly flow in the South China and Sulu Seas. These winds enhance precipitation in the mid to upper South China Sea with additional enhancement as the monsoonal flows reach the Island of Luzon, Philippines. Overall precipitation is enhanced in La Niña years. Even in the "dry" El Niño years, precipitation takes place north of the equator. The Navy Aerosol Analysis and Prediction System (NAAPS) and NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) Aerosol Optical Thickness (AOT) data demonstrate the overall transport pattern of aerosol emissions from Maritime Continent toward the northeast through the South China and Sulu Seas by the monsoonal southwesterly winds.

Figure 1 also suggests the presence of burning and anthropogenic pollution emissions in all years even though burning emissions in El Niño years are significantly enhanced (and often a focus of regional research). The model dust product also indicates significant amounts of residual pollution generated, particularly around Java and Singapore. Burning and anthropogenic emissions are then transported northeast through the South China and Sulu Sea until they are scavenged by cloud and precipitation. At this scale, a systematic southwest to northeast gradient in aerosol particle concentration is evident in a region of moderate precipitation and relatively consistent airflow conditions. Thus it appears possible to examine the convective environment under high and background (low) aerosol loadings.

While the seasonal and inter-annual views provided in Figure 1 provide a tractable conceptual model of large-scale aerosol transport over this region, convection is a meso- to micro-scale

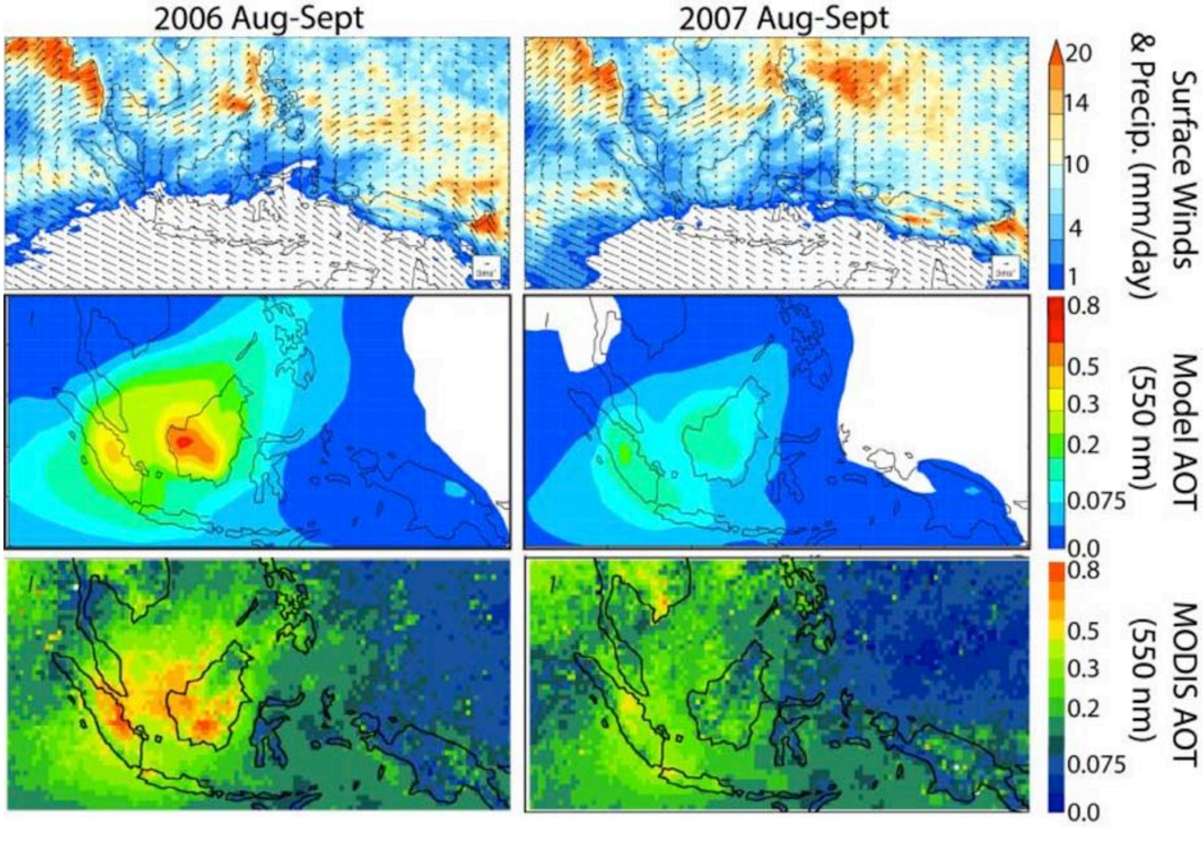

Figure 1. Example meteorological and aerosol fields for August-September periods of the Southwest Monsoon for (left) 2006, and (right) 2007 corresponding to ENSO warm and cold phases, respectively. (Top) NOGAPS surface winds on CMORPH precipitation fields. (Middle and Bottom) Aerosol Optical Thickness (AOT, 550 nm) from the NAAPS model and the MODIS Standard col 5.1 product, respectively. Plots adapted from Xian et al. (2013).

phenomenon. The fine variations in aerosol loadings currently cannot be precisely predicted using model or remote sensing data due to a host of scale and observational challenges. During any given season the Madden Julian Oscillation (MJO) and tropical waves can enhance and suppress convection, or conversely suppress or enhance emissions. Larger scale features such as the MJO are connected to finer scale phenomena such as tropical cyclones, coastal convection, the sea breeze, squall lines, and cold pools. The migration of the MJO across the Maritime Continent is shown in Figure 2 in the form of MTSAT 330Z visible data for periods of the active and suppressed phase of the MJO. Aerosol particle concentrations measured from a platform southwest of Luzon near the Northern Palawan Archipelago (adapted from *Reid et al.*, 2015; ship location denoted with a star in the MTSAT images) are also presented in Figure 2. During this period, the eastward propagating MJO active phase entered and passed through the Maritime Continent. During the more convectively active phases (Sept 19-23), wide spread convection over the South China Sea produced very low, near background aerosol concentration conditions. A break in the convection on September 24-26 resulted in a pulse of smoke and pollution that worked its way across the South China Sea to the region southwest of Luzon. The migrating MJO subsequently corresponded with the development of several Tropical Cyclones (TCs). These TCs simultaneously enhanced aerosol transport to the region through accelerated winds in the South China Sea, and aerosol deposition through scavenging by precipitation. As the MJO left the region, large-scale subsidence from the TCs suppressed convection regionally, leading to a highly concentrated plume of smoke and pollution over the South China Sea. Even within individual events, considerable variability in particle concentrations results from isolated convection and associated cold pools. Thus, as the time series in Figure 2 demonstrates, cloud-aerosol-precipitation feedbacks are influenced by processes on precipitation or microphysical scale and locally by processes on the mesoscale (cold pools, cumulus transport, rainout), both of which are modulated by large scale meteorology.

To account for the overarching meteorology, aerosol-cloud interaction must be investigated at scales much finer than those of mesoscale meteorology. Such an investigation will require study of the physics of convection along with the nature and frequency of the different types of precipitating clouds. Sensitivities of these clouds to aerosol particles depend on a host of environmental variables, including the overall atmospheric stability (*Matsui et al.*, 2006), convective available potential energy (CAPE) (*Storer et al.*, 2010 & 2014), relative humidity (*Khain et al.*, 2008), wind shear (*Fan et al.* 2013), surface fluxes and the radiation budget (*Grant and van den Heever,* 2014). For example, *Storer et al.* (2014) examined the impacts of aerosols on deep convective storms over the East Atlantic Ocean under varying CAPE and static stability conditions. As is evident in Figure 3, enhanced aerosol concentrations tend to impact a number of the characteristics of deep convective clouds, such as the cloud top height. However, the aerosol impact on these clouds is modulated by the presence of CAPE, where the response to aerosol loading is reduced under conditions of greater CAPE. *Grant and van den Heever* (2015) demonstrated the interaction of radiation with aerosol particles sometimes also modulates the response of sea breeze convection to pollution. In their study they found aerosol particles able to enhance updrafts and precipitation amounts from deep convection forming along the sea breeze as it moves in over land. However, if aerosol particles are also present ahead of the propagating sea breeze, their presence reduces the amount of incoming solar radiation reaching the surface, which cools the surface slowing the propagation of the sea breeze. The consequent reduced sea breeze convergence, weakens resultant convection and reduces precipitation.

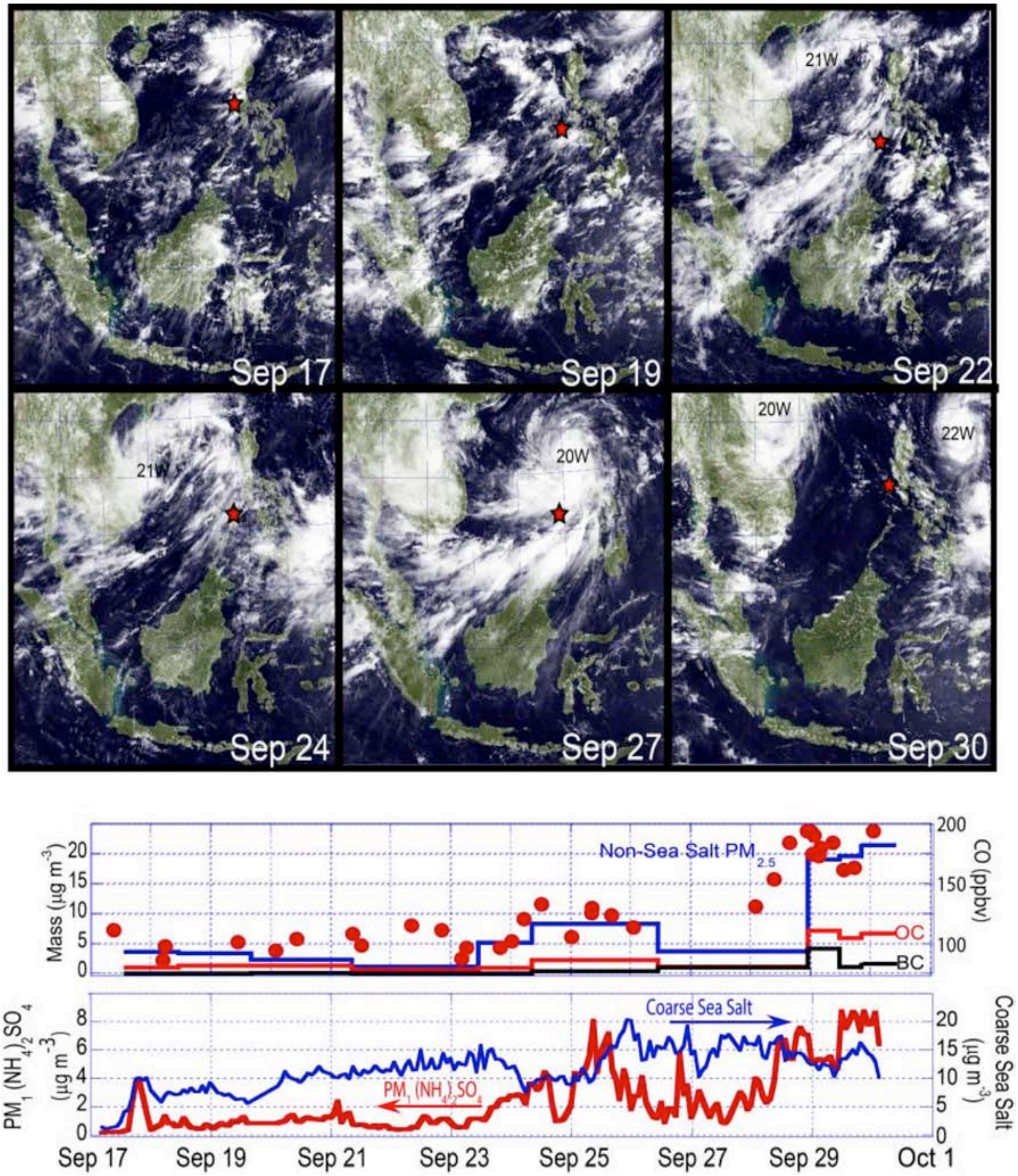

Figure 2. Time series of MTSAT 0330Z visible images for September 17-30, 2013, which corresponded to MJO Phases migrating from 3 through 5. Also shown is the time series of surface level PM$_{2.5}$ (sea salt removed) in blue as measured by the M/Y Vasco southwest of Luzon, Philippines for the same time period (vessel location marked by red star). Figures adapted from *Reid et al.,* (2015). Red and black lines represent organic carbon and black carbon concentrations, respectively.

Another consideration in aerosol-cloud and precipitation relationships is how clouds interact and cloud types organize. Indeed, examination of Figure 2 shows how clouds are organized in bands and clusters. These form as a result of a host of processes including tropical waves, TCs, land sea breezes and cold pools from other convection. *Tao et al*. (2007) found aerosol particle-induced precipitation to vary based on storm type and location, with precipitation being enhanced for tropical oceanic squall lines, reduced from squall lines over mid-latitude continental regions, and unchanged in isolated convection over Florida. A comprehensive study by *Khain et al*. (2008) suggested aerosol particles either increase or decrease precipitation based not only on storm type, but also on the relative humidity and wind shear of the environment, which in turn affects storm type. More recently, *van den Heever et al.* (2011) examined the impact of aerosol particles on a wide range of different cloud types forming in the similar tropical maritime situations. They found enhanced aerosol particle concentrations caused a reduction in precipitation produced by shallow warm rain systems and increase in precipitation produced by deep convective systems. *Grant and van den Heever* (2015) showed aerosol particles to reduce precipitation produced by isolated convective storms over mid-latitudes. However, they found aerosol particles enhanced precipitation produced by multiple convective cell systems due to the effect of aerosols on the cold pools produced by these storm systems. Finally, several recent studies suggest aerosol particles can result in a reduction or enhancement in hurricane intensity depending on whether aerosols impact the outer rain bands or clouds of the eye wall (*Cotton et al.*, 2012; *Herbener et al.*, 2014). All of the aforementioned studies suggest both cloud type and the local environment to be important considerations when examining the impacts of aerosol particles on cloud characteristics and precipitation rates. Furthermore, it must be emphasized that most of the studies reported here are modeling studies. Thus comprehensive observational field observations are now necessary to assess these results.

2.3 Advancing the science through remote sensing

For the very reasons the Philippines represent a useful region to study with the complex mix of aerosols, the presence of clouds and precipitation also makes it a challenging region for remote sensing (*Reid et al*., 2013). While the core goals of CAMP^{2}Ex are scientific process studies, remote sensing will be a strong focal point of CAMP^{2}Ex research as such technology provides most of the aerosol, cloud, and precipitation observing capability for the region. While sensors associated with Terra and the A-train will be ending their operational lifetimes, new sensors have recently started their mission or are in ascension, notably those associated with the NASA/JAXA Global Precipitation Mission (GPM, core satellite launched in February 2014) and NASA's Orbiting carbon Observatory-2 (OCO-2, launched in July 2014). The NASA Venture Class Cyclone Global Navigation Satellite System (CYGNSS) mission is also scheduled to be in operations during the CAMP^{2}Ex campaign. CAMP^{2}Ex will also have collinear goals with the ESA Sentinel and JAXA GOSAT Series. Most importantly, CAMP^{2}Ex will make significant use of the new Japanese Geostationary Himawari-8 platform, which is similar in design to GOES-R. This Advanced Himawari Imager (AHI) on Himawar-8 provides many of the same wavelength bands used in MODIS aerosol and cloud retrievals with regular scans every 10 minutes. Another mission currently planned for launch in 2018 is ESA/JAXA Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) which focuses on the interactions between cloud, radiative and aerosol processes that play a role in climate feedbacks. EarthCARE payload will include a lidar and a W-band cloud profiling radar. Irrespective of whether the actual launch date will be prior or subsequent to CAMP^{2}Ex, the priorities of the EarthCARE Science Team overlap significantly with CAMP^{2}Ex and synergies with EarthCARE Ground Validation are being considered.

The challenges and capabilities of monitoring clouds and aerosol particles in the SE Asian Southwest monsoon are provided in Figure 3, which shows a true color image generated from Himawari 8 AHI. This image highlights the challenge of remote sensing in this region. Note the extensive burning in Borneo with smoke advection into the South China Sea. Clouds are often embedded in the smoke layers. In the western region of the image a convective squall line is forming significant cirrus. Also note the variability in the ocean surface properties near the coastal (littoral) zones. Thus for passive sensors such as MODIS, VIIRS, and AHI this is a challenging region for retrieving cloud and aerosol properties. For visible and near IR observations the radiance (reflectance) measured by the sensors is a function of both scattering angle (i.e., the viewing geometry of the sensor relative to the sun), surface properties, and the atmospheric scattering and absorption which is function of the both molecular, cloud, and aerosols scattering. Retrieval of cloud or aerosol properties requires separation of the clouds/aerosol signal from the clear atmosphere (molecular) and surface contributions. Despite the many spectral bands provided by modern polar orbiting sensors such as MODIS and VIIRS, the retrieval problem remains unconstrained (i.e., the information content in the observations is not sufficient to constrain the solution). For this reason the current MODIS cloud and aerosol optical property retrievals require prior knowledge of the surface properties, the molecular scattering contribution, and the single scatter properties of aerosols and clouds. Additionally, aerosol retrievals require the field of view (FOV) be cloud free as even limited cloud contamination can significantly impact the quality of the aerosol retrieval. Because of these complexities, accurate MODIS Collection 6 dark target aerosol retrievals are limited to regions where the surface properties can be well constrained (i.e., vegetative land and open ocean), which precludes the littoral regions where the surface properties are highly variable.

For the reasons just discussed, passive observations (MODIS/VIIRS/AHI) by themselves will provide limited utility due to the complex mix of clouds and aerosols whose interaction is the focus of this experiment. From a remote sensing perspective, the key to constraining the aerosol and cloud retrievals in the Philippines region will be the integration of data from active (CALIPSO and CloudSat) sensors with the passive observations. CALIOP is the multi-wavelength lidar on the CALIPSO satellite orbiting in formation with MODIS Aqua as part of the A-Train constellation. Being an active system, CALIOP measures vertical profiles of clouds and aerosols. An example of the CALIPSO transect of the Himawari-8 image is presented in the bottom of Figure 3. Note the vertically extensive aerosol layer (light blue region) in the latitude range between -6° to -2° with cloud formation within the aerosol (smoke) layer starting around – 2° latitude.

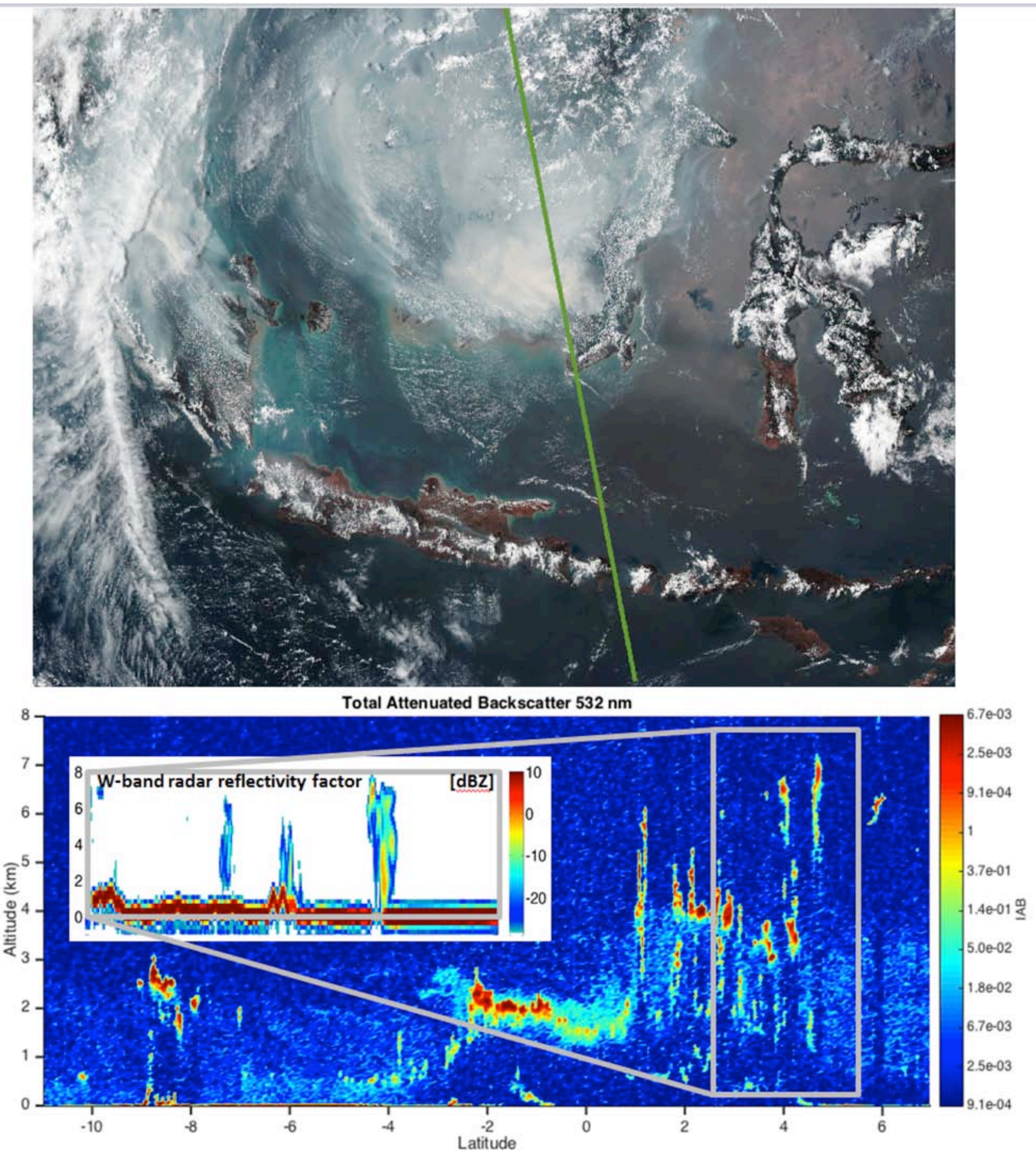

Figure 3. Figure 3 A true color image generated from the recently launched next generation geo-stationary imager (Himawari-8) presented in the top image. Notice the extensive smoke over the Borneo region in the center of the image. The green line is the CALIPSO transect at the time of the image on September 10th 2015. The CALIOP 532 nm attenuated backscatter is presented in the bottom image. Notice the extensive vertical extent of the smoke (light blue regions). In this particular case, smoke is so dense that at latitudes -2 to 2 the beam many be severely attenuated. Also shown is the corresponding CloudSat reflectivity for the group of cloud just north of Borneo.

Near the northern region of the image CALIOP detects smoke from the surface up to 4 km with clouds forming near the top of the smoke layer. The lidar observations do have limitations: the lidar beam attenuates in thicker clouds (i.e., optical depths greater than 3.0), as it does in this case between -2° and +6° latitude. Indeed, it is in cloudy scenes where the synergy between the lidar on CALIPSO and the Cloud Profiling Radar (CPR) on CloudSat becomes evident: the two orbit in close formation so they observe the same area within approximately 2 minutes. One example is shown in the blowout box between 2.7° and 5.5° latitude where the W-band CPR profiles the cloud structure below cloud top where the lidar becomes attenuated. In this case the radar data show the north-most cloud observed by the lidar was a cumulus congestus with significant precipitation. On the other hand, the south-most cloud was a non-precipitating mid-level cloud. The pairing of lidar and cloud radar profiles is the basis of several A-Train combined products and of the algorithms being developed for EarthCARE (e.g., *Mace and Zhang*, 2014, *Ceccaldi et al.*, 2013, *Delanoë et al.*, 2013). The complementary radar and lidar enables association of the occurrence of specific types of cloud systems to the surrounding aerosol particle environment. For optically thin clouds detected by both, it also enables more accurate estimation of hydrometeor properties because of the differential spectral response at multiple wavelengths. For moderate to heavy precipitation, the W-band radar data become substantially attenuated. Thus intense storms are best observed with a combination of radar frequencies, such as the Ku- and Ka-band Dual-frequency Precipitation Radar (DPR) on board GPM core satellite. In general, the combination of lidar and the three radar frequencies has proved to be essential for two purposes. First, these data enable reliable detection of the entire cloud structure from the thinnest to the thickest clouds (see Figure 4 panels a & b). Second, these data also provide information on cloud microphysics due to differential spectral response where two or more of these channels are able to detect hydrometeors.

Similar to the passive sensors, quantitative retrievals of the aerosol and cloud properties through measurements by active instruments require assumptions regarding the scattering properties of the aerosols and clouds, which can vary significantly. Thus the optimal retrieval for this experiment will combine the active and passive sensors as currently done by the A-Train and by GPM. Each of the two is already using standard retrievals with algorithms that combine active and passive observations. Furthermore, since GPM launch in 2014, the development of new algorithms combining the data from the two missions (and sensors in geostationary orbit) has started proving to be useful. An example of the information obtained by combining CloudSat and GPM is shown in Figure 4, panel c. The simultaneous availability of measurements by 3 radar frequencies guarantees every portion of a storm will be observed by one or more channels. When more than one channel generates useful data, differential signatures provide additional information on hydrometeor type, and mean particle size (e.g., *Leinonen et al.*, 2012) due to the different scattering and extinction properties of various hydrometeors. Combining active and passive remote sensing measurements enables reduction in the uncertainties of the retrieved products beyond data retrieved from individual sensors (e.g., *Munchak and Kummerow*, 2011).

A limitation of the polar orbiting observations is that each platform only provides a "snapshot" of the region once or twice per day. Since CAMP^{2}Ex is focused on process studies of the interaction of clouds, aerosol, and precipitation, observing the time evolution of aerosol and cloud properties is critical. Geostationary observations provide this capability. Previously, geostationary sensors lacked the needed spectral channels and calibration accuracy to provide well characterized aerosol and cloud retrievals. However, the recent launch of the Japanese Himawari-8 satellite provides the first MODIS-like observations from geostationary orbit. The main sensor on Himawari-8 is AHI, which is almost identical to the next generation US GOES-R sensor (ABI). AHI provides full disk 10-minute observations at 1 km resolution for visible and 2 km resolution for IR channels. The true color image presented in Figure 3 was generated from AHI data. Since AHI has almost the same spectral coverage in the visible as MODIS, near-MODIS quality cloud and aerosol retrievals can be generated every 10 minutes. Leveraging the additional information content in the temporal domain provides the potential to greatly improve the aerosol and cloud retrievals as observations time evolution can be used to better constrain the surface properties in littoral regions, such as the Philippines.

Air motion observations are the last type of remote sensing measurements essential for CAMP^{2}Ex objectives. Ocean surface winds (either horizontal wind velocity alone, or the meridional and zonal components) are routinely observed by active and passive sensors (e.g., RapidScat, ASCAT, SSMI/S) and assimilated in general circulation models. In the region of interest, the abundance of clouds and water vapor at several levels also enable use of products derived from imagers in GEO and LEO, in the IR and visible ranges to obtain horizontal wind vectors at various altitudes (e.g., *Velden et al*., 2012). The EarthCARE CPR will be the first spaceborne cloud radar with Doppler capability to measure the vertical velocities within cloud. However, these measurements from space are not expected to have sufficient temporal and spatial resolution to resolve the dynamics of the clouds of interest in CAMP^{2}Ex. The field experiment will therefore rely primarily on wind data from airborne or ground based Doppler radars, and in-situ wind measurements.

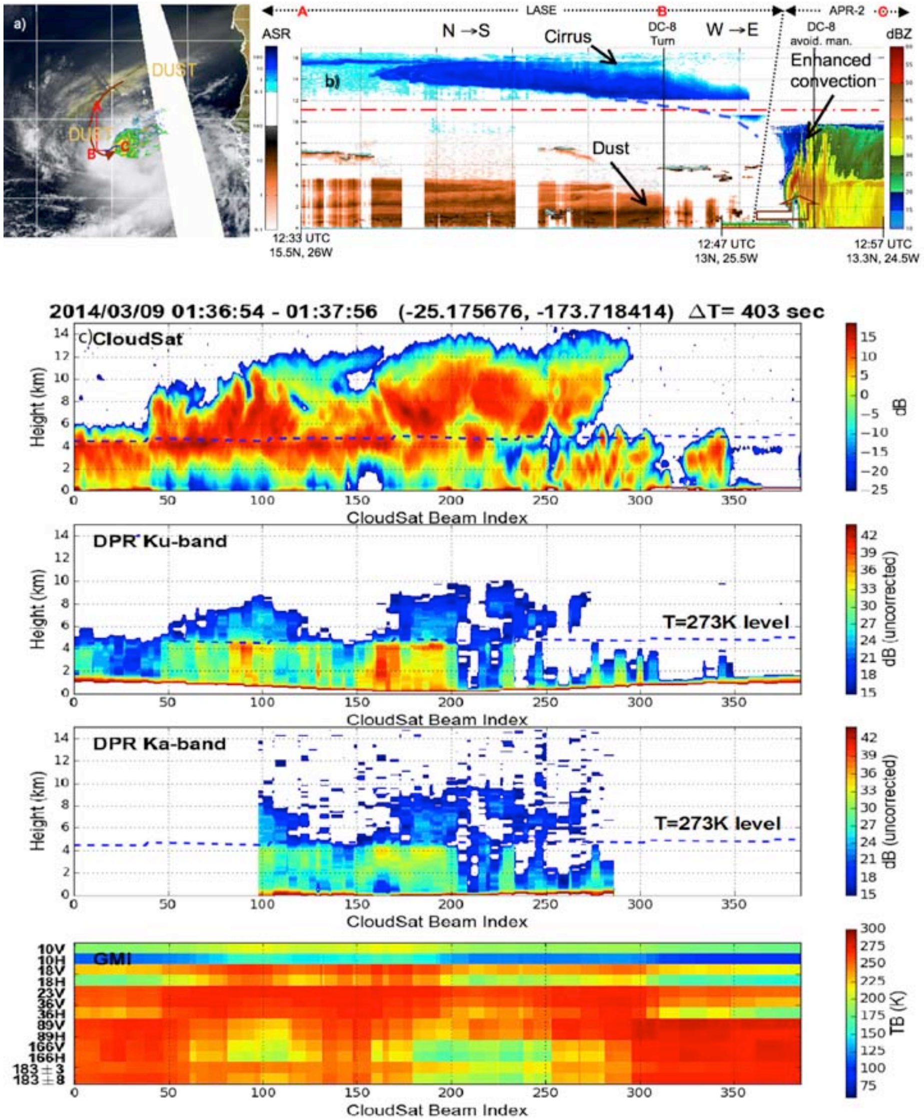

Figure 4. (a) and (b) remote sensing measurements of Tropical Depression #8 on 12 Sep 2006, later to become Hurricane Helene. (a) *Terra* image shows the cloud system organized around the center of circulation just south of Cape Verde, together with the dust layer approaching from the Saharan region. The DC-8 approached the system from the northwest. The ground track is shown in red (LASE data available) and blue (APR-2 data available). Radar reflectivity from the TOGA radar on Praia is overlaid in the area within range and shows a line of convective cells along the western boundary of the storm. (b) Vertical section of LASE's aerosol scattering ratio and (right) APR-2's Ku-band reflectivity. LASE data are attenuated when the DC-8 enters the cirrus shield (dotted line marks the approximate boundary). DC-8 path (red dashed–dotted line) and approximate cloud base (blue dashed line) are shown for reference. The brown arrows indicate the likely path of the dust layer into the convective system. Dual-frequency radar observations show that small ice crystals dominated the cirrus "ahead" of the convective cells (blue area), while larger crystals and aggregates are present immediately "behind" it (green area). (c) Example of collocated CloudSat and GPM collocated measurements of a convective system acquired on September 3, 2014 in the southern Pacific. From top to bottom: W-band Cloud Profiling Radar measured reflectivity, GPM Dual-Frequency Precipitation Radar Ku- and Ka-band measured reflectivity, and brightness temperatures at all channels of the GPM Microwave Imager along the same section.

3.0 Scientific Goals and Objectives

The overall scientific goal of CAMP^{2}Ex is to characterize the role of anthropogenic and natural aerosol particles in modulating the frequency and amount of warm and mixed phase precipitation in the vicinity of the Philippines during the Southwest Monsoon.

Evidence suggests the impact of aerosol particles on precipitation is strongly influenced by background meteorology, aerosol type, as well as the vertical and horizontal distribution of aerosol particles and clouds. Thus it is likely the role of aerosol particles in modulating precipitation has a regional dependency. While many modeling investigations have contributed important insights into the role that aerosol particles can play in modifying cloud and precipitation properties, observational data to both constrain and evaluate models is lacking. This lack of observations is particularly true in the Philippines and surrounding areas. Satellite observations provide an important source of data. However, their quantitative interpretation in terms of atmospheric and surface properties is severely hampered by the large and incomplete quantification of their error characteristics, particularly in the complex and heterogeneous environment of monsoonal flows. Additional constraints in deriving atmospheric and surface properties from satellite observations can be provided through detailed field observations. In total, what motivates the *CAMP^{2}Ex* aircraft measurement campaign are the impacts that aerosol particles may have in modulating warm precipitation over the Philippines during the Southwest Monsoon, the combination of important aerosol sources and meteorological conditions of the region, the complexity of these conditions, as well as the need to constrain and evaluate model simulations and satellite observations. Thus the central objective of CAMP^{2}Ex:

CAMP^{2}Ex will provide a comprehensive 4-D observational view of the environment of the Philippines and its neighboring waters in terms of microphysical, hydrological, dynamical, thermodynamical and radiative properties, targeting the environment of shallow cumulus and cumulus congestus clouds.

Shallow cumulus and cumulus congestus clouds are the key cloud types associated with the overall scientific goal of *CAMP^{2}Ex*. Other cloud types that may be encountered include deep convection, as they transform from congestus, low stratiform clouds and even thin mid-level clouds. These cloud types, however, are considered to be secondary targets. The *CAMP^{2}Ex* data collection approach aims to provide the observations needed to address the overall scientific goal of *CAMP^{2}Ex.* To help facilitate strategies for data collection, the focus will be on several pressing questions and tasks that need to be addressed. These questions and tasks are divided into three areas: (1) aerosol and cloud microphysics, (2) aerosol and cloud radiation, and (3) meteorology relationships between aerosol and cloud lifecycle. These research areas are described in detail in the subsections below. Note, these divisions are actually strongly intertwined; they only exist to help compartmentalize this presentation.

In addition to the overall scientific goal of *CAMP^{2}Ex*, our Philippine partners will use data collected during *CAMP^{2}Ex* for their own research. This includes research and applications in natural hazards, physical oceanography, air quality, and land use as described in more detail below.

3.1 ***Aerosol and Cloud Microphysics***

Core to CAMP^{2}Ex is the need to develop a working knowledge of how aerosol particles influence warm and, secondarily, ice cloud physics. Nominally this component addresses the questions:

a) *How do the composition and concentrations of aerosol particles (including those of CCN and, secondarily, IN) affect the optical and microphysical properties of shallow cumulus and congestus clouds and the development of precipitation from these clouds?*
b) *How does the composition and concentration of aerosol particles (including those of CCN and, secondarily, IN) impact the latent heating and invigoration of congestus clouds, and hence their potential transition to deep convection and larger precipitation rates?*

Although it has been well established that aerosols can have an important influence on smaller-scale cloud systems, the degree to which they can influence an entire field of such cloud systems, or to which these cloud systems can grow to deeper, larger convective storms has not been well established. Past modeling studies have suggested that aerosols can impact the transitions from stratocumulus decks to fields of more isolated cumulus clouds, as well as the interactions between cumulus entities through their impacts on updrafts, subsidence, cloud-top entrainment and cold pool interactions (e.g. *Xue et al*., 2008; *Saleeby et al*., 2015). Also, if aerosols act to inhibit the initial collision-coalescence process by delaying the development of precipitation-sized embryos, it is possible that such convective clouds will ascend to higher heights, thus generating larger, deeper convective cells and more intense rainfall. As discussed above, the presence of aerosol particles appear to support the more frequent development of congestus clouds above the freezing level, from where additional latent heat release in association with the formation of ice strengthens the updraft (e.g., *Li et al*., 2010; *Sheffield et al*., 2015). Here, composition influences whether aerosol particles may serve as CCN, IN or both, which in turn influences the type of hydrometeors formed. The impact of aerosol particles on precipitation rates may impact the evolution of cold pools from evaporated precipitation. These cold pools contribute to the development of new convective cells, and hence can feedback into the dynamics of the system, which in turn will affect cloud properties. As described in the next section, the influence of aerosol particles on cloud microphysics and optical properties, can have a profound influence on radiative heating rates in the atmosphere and surface, which impact the dynamics of the system.

3.2 *Cloud and Aerosol Radiation*

Electromagnetic radiation is the energy that drives our weather and climate system. It is also the only quantity that satellites directly measure. Understanding the transfer of radiative energy and the interpretation of satellite data is necessary to achieving the overall scientific goal of CAMP^{2}Ex. Gaining this understanding is impeded by the complexity in aerosol and cloud optical properties, as well as the strong spatial heterogeneity of these properties found in the Maritime Continent. Specific to the region, the CAMP^{2}Ex field campaign targets the following broad questions:

a) *How does the observed spatial heterogeneity in the aerosol and cloud field impact the spatial distribution of radiative heating rates in the atmosphere and the surface?*
b) *How do observed changes in the aerosol field directly and indirectly impact the spatial and temporal distribution of radiative heating rates in the atmosphere and at the surface?*
c) *How do these changes in the radiative heating rates feedback into the evolution of the aerosol, cloud, and precipitation fields?*
d) *To what extent does the heterogeneity of the atmosphere impede the use of satellite remotely sensed products for quantifying aerosol-induced changes to cloud and precipitation properties?*

Section 3.1 describes several pathways by which aerosol particles can modify cloud and precipitation properties. These pathways couple with radiative pathways as well. For example, the introduction of a homogeneous layer of aerosol particles reduces the amount of solar radiation reaching the surface, and modifies the vertical distribution of radiative heating. Here, the composition of aerosol particles can become very important as carbonaceous aerosols absorb more radiation and might have different impacts on storm dynamics than other types of aerosols. For example, such absorbing aerosols can enhance the stability of the layer of the atmosphere in which they reside, thereby influencing cloud development and the vertical height to which they ascend. As noted in Section 3.1, changes in the aerosol field induce changes in both the cloud microphysical and optical properties of the cloud and the overall structure and evolution of the cloud. These changes to the cloud field impact the amount of absorbed and emitted radiation throughout the atmosphere and surface, along with radiative heating rates.

Satellite remotely sensed products assume horizontal homogeneity in the radiative transfer used for retrieving cloud and aerosol properties. The breakdown of this assumption under heterogeneous conditions is known to lead to biases in the retrieved products. *Di Girolamo et al.*, (2010) showed, based on satellite observations, the deviations of the radiation field from heterogeneity in the region is largest around the Philippines. *Liang et al.*, (2015) have recently confirmed the bias in warm oceanic cloud drop effective radius derived from satellite is largest over this region. Since biases in the retrievals co-vary with the underlying heterogeneity of the scene, we cannot decouple true space-time variability found in nature from the space-time variability in the bias. This issue needs to be further understood and quantified to increase the scientific utility of our satellite datasets.

3.3 *Meteorological Relationships Between Aerosol and Cloud Lifecycle*

While the objective of CAMP^{2}Ex is centered on observations of microphysics and radiation, the mission must nevertheless address some aspects of regional meteorology and, in particular, how meteorology can confound aerosol-cloud interaction studies. This class of objectives requires recognition that many non-causal relationships exist. At the same time aerosol particle induced changes in clouds and precipitation may also feedback into aerosol particle production, transport and removal. For example, tipping points in precipitation initiation or airflow patterns around clouds (e.g., aerosol vertical lifting, up- and down-drafts, cold pools etc.) may exist, which could regulate cloud and ice nuclei concentrations. Sufficient measurements need to be made in order to untangle these relationships on a statistically significant basis.

As laid out in Section 2.1, the sensitivity of clouds to aerosol particles is dependent on a host of environmental variables including wind shear, CAPE and the stability of dry layers. Patterns of aerosol particle and cloud lifecycle are also tightly interwoven. Enhanced convection leads to lower emissions and/or shorter aerosol lifetime due to precipitation scavenging. Dry periods, particularly prolonged dry periods, lead to higher emissions and longer aerosol particle lifetime. Even as pulses of polluted air are transported from islands, the overall meteorological structure evolves with them. To reach the goal of CAMP^{2}Ex, we must understand and account for the co-variability between meteorological, aerosol particle and cloud properties. *The following questions need to be addressed:*

a) *To what extent are perceived aerosol-cloud interactions studies confounded and/or modulated by co-varying meteorology?*
b) *By what meteorological mechanisms do "polluted" conditions transition into "background" conditions?*
c) *What meteorological features are the most influential in regulating the distribution of aerosol particles throughout the atmosphere and ultimately aerosol lifecycle (sources, sinks, and advection)?*
d) *What is the statistical variability in aerosol particle concentrations within an airmass and to what extent is knowledge of large-scale aerosol fields and wet deposition in the region sufficient to predict regions of anthropogencially induced aerosol-cloud-precipitation interaction?*

Questions such as these cannot be completely addressed by any single airborne campaign. However, given the A-Train record along with new observations from GPM and ever increasing modeling capabilities, it is anticipated CAMP^{2}Ex will provide at least some of the data needed to answer these questions. The constant oscillation between monsoon active phases and breaks by the passage of tropical waves force the meteorological and aerosol environment at large scales. CAMP^{2}Ex will include activities to investigate and evaluate the representation of the environment by satellite and model products at a multitude of scales.

At intermediate scales, the processes by which island aerosol particle emissions migrate into the monsoonal flow is often a result of land–sea breezes, which also influence convection. Thus, it is likely a stochastic component to the aerosol-cloud interaction includes coherent "puffs" of perturbed meteorology and aerosol particles, which propagate within the monsoonal flow. CAMP^{2}Ex will provide the first ever estimates of this stochastic variability, structure, and length scales.

Finally, aerosol-cloud interactions are known to involve fine scale processes, which are difficult to incorporate into cloud-resolving and mesoscale models, let alone climate models. These processes are also largely unobservable from space. For example, convection generates cold pools, which, in turn, spawn new cycles of convection. At the same time, cold pools influence aerosol particle concentrations and moisture fields ahead of and within cloud updraft zones. Modeling studies by *Grant and van den Heever*, (2015) for mid-latitude systems found changes to the moisture profile always induced larger changes in precipitation than did variations in aerosol particle concentrations. This finding begs the question as to what extent are aerosol impacts and finer scale meteorology confounded? These investigators also found multicells to be sensitive to perturbations in aerosol particle properties, while supercells appear less sensitive to changes in aerosol particle properties. This difference is likely a result the significant impact aerosol particles have on cold pool forcing, while supercells are predominantly dynamically driven. Cold pools are thought to be warmer in the presence of enhanced aerosol concentrations due to the populations of fewer but larger raindrops. Populations of larger droplets evaporate more slowly than those consisting of more numerous smaller drops (e.g., *Berg et al.,* 2008; *Saleeby et al.,* 2010; *May et al*., 2011; *Storer and van den Heever*, 2013). Warmer cold pools stay closer to their parent storms, thereby supporting longer-lived, stronger storms through positive feedback. While such microscale phenomena have been studied at mid-latitudes, they are less studied in tropical monsoonal flows. *Reid et al.,* (2015) found cold pools to effectively remove aerosol particles from the boundary layer ahead of the main cells. In studies of haboobs, *Seigel and van den Heever*, (2012) found dust within the environment ahead of the cold pool is lifted up and over the cold pool, while very little of the significant dust mass lifted within the cold pool was ingested into the cloud base updraft. CAMP^{2}Ex will provide the first airborne observations of these finer scale phenomena and observe variability in aerosol particle distribution in the vicinity of clouds, convective cells, and cold pools.

3.4 ***Philippine Science Objectives***

Most of NASA's objectives in CAMP^{2}Ex focus on improving the understanding of individual cloud and aerosol process, as well as improvement of satellite products. On the other hand, Philippine scientists are more interested in the ramifications of monsoonal meteorology on regional hydrology, oceanography, and air quality. Key CAMP^{2}Ex partners include the Manila Observatory, the Philippines Atmospheric Geophysical and Astronomical Services Administration (PAGASA), and the University of the Philippines. Philippine scientists and policymakers alike, such as from these institutions, need improved estimates of the when's, where's and how's of significant precipitation events and droughts. Satellite products, which are often tuned for providing consistent global estimates of rainfall or air pollution loading, require application and validation for direct Philippine use. At the same time satellite and airborne products may aid in the development and verification of Philippine data products, such as from regional weather radars, which in turn can improve Philippine environmental monitoring for both basic research and natural hazards.

Philippine scientists are also posing key process studies as part of CAMP^{2}Ex. While the NASA science focuses on aerosol impacts on precipitation, Philippine scientists wish to evaluate the extent to which land use change may contribute to the perceived sensitivities of convection to large-scale meteorology and aerosol particles. This Philippine led science component will account for one potential confounder in the system; the role of land use change in modulating precipitation. Rapid economic development in SE Asian counties such the Philippines has drastically changed land use characteristics. This includes deforestation and urbanization. Such land use change impacts surface momentum, sensible and latent heat fluxes, as well as aerosol emissions patterns. Hypotheses suggest deforestation and urbanization result in decreases and increases in roughness length, respectively, as well as substantial changes to the surface and latent heat flux. At the same time, these changes result in increased aerosol emissions, which may also impact clouds and precipitation. CAMP^{2}Ex's focus on monsoonal precipitation also has relationships to physical oceanography, notably how fresh water fluxes impact ocean salinity and the formation of upper ocean boundary layers. This in turn has ramifications for air-sea fluxes and hence convection.

4.0 Campaign Location, Timing and Extent

Based on several Philippines site visits, the most feasible location for a base of operations is Subic Bay from late July through early September, 2018. The NASA P-3B is the tentatively scheduled platform. Roughly two 8-11 hour flights are anticipated per week with three additional flights in reserve for optimum conditions. A total of ~15 flights and ~150 hours for research are expected. This choice of timing and basing location is a compromise between science objectives and flight logistics including availability of research platforms, hangar/laboratory/office space, maintenance field facilities, and science team housing, security, access etc. As mentioned above, the Southwest Monsoon has southwesterly winds over the East Philippine Sea, bringing air from Borneo, Sumatra and the Thai Peninsula over the entire Philippine island chain. The basic science objectives can be met by flying within Philippine Airspace, controlled by the Manila Flight Information Region (FIR, Figure 5). To study important atmospheric processes in the Southwest Monsoon, CAMP^{2}Ex intends to fly over the ocean primarily west of the Philippines from northern Luzon, along the Palawan Archipelago and into the Celebes Sea. Thus target areas include the East Philippine, Sulu, and Celebes Seas. On a few flights, the P-3B may enter the typhoon development regions of the Western Pacific.

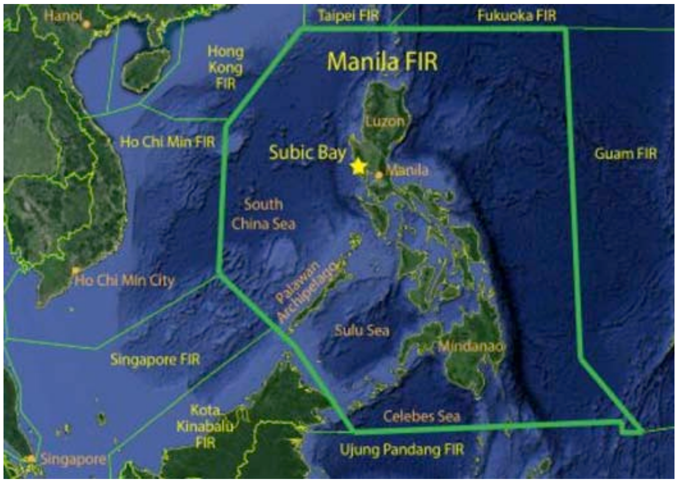

Figure 5. Manila Flight Information Region (FIR) with surrounding FIR boundaries. Also marked is the proposed Subic Bay base of operations.

The Southwest Monsoon typically occurs from late April through early to mid-October, and largely coincides with the tropical cyclone season. A primary consideration for the mission includes the timing of biomass burning emissions, which peak in August and September. Peak burning progresses eastward in time, with agricultural dominated burning in Central Sumatra Riau and western Borneo/Sarawak being active in August with southern Sumatra and southern

Borneo/Kalimantan and Sulawesi progressively later into September and early October (*Reid et al.,* 2012). To maximize aerosol variability the mission should ideally be centered on early September. However, platform scheduling dictates an earlier mission. Consequently, CAMP^{2}Ex will focus on pollution emissions and the early burning season in Central Sumatra. A second consideration is the ~45 day period of the Madden Julian Oscillation. This eastward propagating field of convection has a large influence on precipitation, smoke emissions and aerosol transport in the region. The MJO is typically at its weakest during August. Thus, investigating the impact of the MJO is secondary objective. Nevertheless, the experimental plan will be flexible enough to take advantage of an atypically strong MJO during August 2018.

5.0 Measurement Philosophy and Requirements

The primary set of measurements required in this airborne experiment is defined by the need to characterize the cloud, precipitation and aerosol particle properties, as well as the associated atmospheric and cloud dynamics and the fluxes of solar and terrestrial radiation. While this is an aerosol-cloud-precipitation mission, a primary concern is the appropriate consideration for variations in the meteorology. Aircraft data and flight time will be dominated by column characterizing measurements such as radars, lidars, and dropsondes such that gradients in meteorology, cloud properties and aerosol concentrations are measured. In situ cloud microphysics will also play an important role and the capability of characterizing precipitation and mixed phase cloud properties is also required. Aerosol and gas chemical composition measurements will focus on the identification of the origin of their air mass rather than the nuances of chemical processes.

Minimum measurement requirements for the aircraft are:

- Cloud and precipitation structure and in-cloud vertical motion will be observed using cloud and precipitation Doppler radars and remote sensing imagers; a multi-channel microwave radiometer and/or sounder may also be used.
- Aerosol layer structure and the vertical movement of air out of cloud tops will be measured by an aerosol lidar; an aerosol/cloud polarimeter may also be included.
- Three-dimensional characterization of fundamental atmospheric state variables (pressure, temperature, humidity, winds, etc) will be made using in-situ probes and by deploying dropsondes.
- In-situ cloud and precipitation measurements of liquid and ice water content, size distribution, and resulting estimates of precipitation rate will be made using in-situ probes.
- Aerosol measurements of size and composition will be made using in-situ aerosol sizers and a possible combination of aerosol mass spectrometer and/or liquid chromatograph.
- Energy fluxes and surface temperature using solar and IR radiometers.
- Aerosol particle microphysical and radiative properties measurements to better interpret collected remote sensing data, such as scattering, hygroscopicity/CCN and absorption and/or black carbon estimates using a nephelometer, CCN spectrometer, and absorbing aerosol sensor.
- Measurements of atmospheric gas phase constituents and aerosol chemistry in so far as they can identify air mass sources. These may include CO and O_3.

In addition to these minimum measurements requirements, additional instruments will be selected as resources allow. Preference is given to technologies with a good compromise between heritage on the P-3B or similar aircraft, accuracy, and rapid time constant. Potential measurements include (alphabetical order):

- Cloud liquid water sampling and analysis
- Hyperspectral, stereoscopic, or polarometeric imaging
- Ice nuclei
- Cirrus monitoring by lidar
- Quantitative aerosol speciation
- Aerosol particle and thin cloud properties by sun photometry
- Turbulent fluxes

Finally, several spaces will be reserved for guest measurements such as from international partners, the PISTON science team, or other NASA projects or missions (e.g., Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations-CALIPSO, CloudSat, Cyclone Global Navigation Satellite System-CYGNSS, Global Precipitation Measurement mission-GPM, EarthCARE).

In addition to specific airborne instrumentation, CAMP^{2}Ex will also have remote sensing and modeling requirements. It is recognized that the next generation of geostationary satellites, such as the imager on Himawari -8 will provide unprecedented views of regional fire activity, aerosol transport and cloud lifecycle. Also by the time of CAMP^{2}Ex deployment, GPM products will have matured, and CYGNSS observations of surface wind speed will be available. Combined, the upcoming satellite sensors will provide much needed regional monitoring.

Flight planning and interpretation of CAMP^{2}Ex results will require modeling support. The meteorology of the Maritime Content is well known to be among the most challenging to monitor and model in the world. Models have significant difficulty in appropriately resolving the diurnal nature of convection in coastal or open ocean regions. Global models can capture the largest features of wind and precipitation, but fine scale features that dictate aerosol-cloud interaction such as the sea breeze, coastal convection, squall lines, cold pools and mesoscale convective complexes require higher resolution simulations. However, such simulations have difficulty assimilating or verifying utilizing the limited observations available. To cope with this situation, CAMP^{2}Ex will make us of various modeling approaches focusing specifically on finer mesoscale and cloud resolving scales. Cooperation is anticipated with PISTON on the influences of tropical wave scale convection.

6.0 Relationships to Other Programs and Studies.

The CAMP^{2}Ex mission will be executed in a manner so as to benefit a number of NASA satellite missions and cooperatively advance regional science in climate change, tropical meteorology and numerical weather prediction. Notably, flights will be coordinated with the Global Precipitation Mission (GPM) and the A-train sensors such as CALIPSO and CloudSat. It is expected that at mission execution the NASA Cyclone Global Navigation Satellite System (CYGNSS) and ESA Sentinel 5P will be operating. Finally, geostationary JMA HIMAWARI-8 aerosol and cloud products will be mature adding a significant temporal dimension to aerosol - cloud interaction studies.

The CAMP^{2}Ex program is also collinear with aspects of the "Year of the Maritime Continent," an international consortium of investigators studying the Maritime Content region for 2018-2019. CAMP^{2}Ex will coordinate most closely with the Office of Naval Research sponsored Propagation of Intra-Seasonal Tropical Oscillations (PISTON). PISTON's overarching goal is to improve understanding and numerical simulation of multi-scale tropical convection and the role of air-sea and land-sea interactions in tropical archipelagos. PISTON will focus on numerical modeling and may also provide a UNOLS global class research vessel to the region during a portion of the CAMP^{2}Ex flight operations. Given the sensitivities of aerosol-cloud interaction to the underlying meteorology, collaboration between CAMP^{2}Ex and PISTON is anticipated.

7.0 Benefits to Philippines and the Scientific Community.

This airborne campaign will bring much needed scientific attention to regional environmental problems, with benefits to scientists, policy makers and the local populations. The campaign will extend and deepen the scientific collaboration between Filipino and US science communities on weather and climate change issues. This campaign will specifically benefit the Philippines by:

- Improvement to our understanding of the regional Earth system through collaborative research, especially with regard to weather, climate, atmospheric composition and long-range atmospheric transport.
- Facilitation of local water and emergency response management through improving our understanding of how precipitation processes, and hence drought and flooding, will change with changing climate.
- Development of unique and comprehensive data sets that will be freely available via the internet; these data will be available to Filipino scientists and students for the foreseeable future.
- Use of the data for verification of remote sensing and modeling data to enhance their use for hazards, weather and climate forecasting.
- Exposure of Philippine scientists to cutting edge earth system science technology, including the availability of training (including short courses) on how to access and use remote sensing data.
- Presentation or research aircraft construction and use via an "open house" for students, researchers and VIPs.
- Providing access to more than 50 world-class scientific and technical personnel in-country for ~1.5 months and available for scientific interactions and development of collaborations.
- Active participation of Philippine scientists during all phases of the project including planning, the field campaign, data analysis and modeling, and publication of results.
- Presentation of key science results at an international science conference for key stakeholders, researchers and students.

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